Optimal receiver cost and wavelength number minimization in all-optical ring networks

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Abstract—**Reducing both power consumption and the ecological impact of networks has become a priority. Solutions which allow us to reduce these factors are based on all-optical technologies. All-optical rings are beginning to be deployed as metropolitan networks and new more energy efficient equipments are being proposed. We present one of these equipments and explain how to reduce the CAPEX of such networks by properly dimensioning them. Receivers located in nodes read information from wavelengths. We study a dimensioning problem which consists in minimizing the number of wavelengths and the total number of receivers in a ring for a given traffic matrix. We prove that this problem is NP-complete and propose a heuristic algorithm. The solution has been validated under realistic traffic conditions and achieved near-optimal results. The solution could be extended to wider networks if we consider working with multi-ring networks.**

I. INTRODUCTION

Metropolitan networks carry traffic generated by distributed services such as *VoIP* (Voice over IP) or *VOD* (Video On Demand) among others. Since these services require an ever-growing bit rates, the network should provide a high bandwidth capacity. For this reason current metropolitan networks partly use optical technologies, which are based on low-layer protocols such as *Synchronous Optical NETwork* (SONET) and *Synchronous Digital Hierarchy* (SDH) [16]. Generally, their architecture is a hybrid ring, i.e. a ring with optical fiber links and optoelectronic nodes. Despite the fact that the fiber offers low attenuation rate, the optical signal is stopped and regenerated at each node since optoelectronic devices do not allow the light to pass transparently. Moreover the study [5] shows that the power consumption of the current electronic devices depends on the amount of traffic passing through them. The optoelectronic solution does not meet the increasing demand well. In order to reduce the power consumption and thus reduce both the *OPerationnal EXpenditure* (OPEX) and the ecological impact of metropolitan networks, future metropolitan networks will include all-optical technology [25]. Unlike hybrid rings, all-optical rings are made of *transparent* nodes. In these nodes the optical signal can either pass through or be dropped off. According to [5], power requirements in the photonic domain are almost independent of the bit rate.

The DOROthéE[1] project aims to reduce the *CAPital EXpenditure* (CAPEX) of metropolitan networks with low ecological impact by properly dimensioning them. We deal with the new dimensioning constraints arising due to the all-optical technology and try to understand the emerging problems.

We study one of the identified problems for a ring topology which is, as we have said before, the most commonly used topology for optical metropolitan networks. The dimensioning process of an all-optical network consists in both minimizing the number of wavelengths used and simplifying the internal structure of nodes.

The rest of this paper is organized as follows. Section II contains an overview of the all-optical technology and a survey of the research studies. The node architecture presented in [25] has been chosen as a reference for most of the performed studies. In Section III we describe a new architecture for all-optical nodes. This architecture was introduced in [7]. To the best of our knowledge there is no dimensioning work dealing with this architecture. In Section IV we introduce an identified dimensioning problem which we call the *Minimum WaveLength Problem* (MWLP). We study its complexity in Section V. In Section VI we present a heuristic algorithm which solves the MWLP and comment the obtained results. Finally we conclude and outline perspectives.

II. RELATED WORK

In this section we give an overview of the all-optical technologies and present the research that has been carried out and which can be associated with our work.

In SONET/SDH networks traffic is carried between nodes on the different wavelengths using *Wavelength-Division Multiplexing* (WDM) technology. Each wavelength is a high speed channel with a fixed transmission rate OC-N where N indicates the wavelength capacity (ex: OC-192 = $192 \cdot 51.84 = 9.952$ Mbps). Using *Time-Division Multiplexing* (TDM) a wavelength can carry multiple time-slot channels. Time-slot channel transmission rates can be variable (ex: OC-3, OC-8). We note OC-min the size of the smallest time-slot channel.

The ratio between OC-N (WDM channel) and OC-min (TDM channel) is called *grooming ratio*. We will use the grooming ratio value as wavelength capacity.

[1]DOROthéE is a Digiteo project financed by the Ile-de-France region.

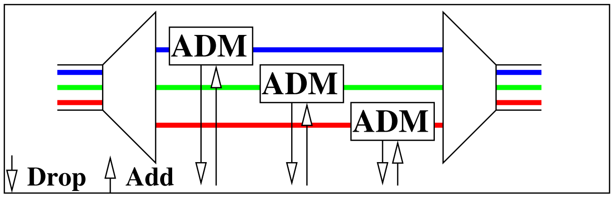

Fig. 1. ADM node architecture

Current SONET/SDH networks are point-to-point networks. Traffic is added/dropped to/from the wavelength using electronic *Add-Drop Multiplexer* (ADM). Fig. 1 depicts an architecture of nodes provided only with ADMs. One ADM is required for each wavelength at each node. The optical signal is stopped at each node even if the node does not need to add/drop traffic to/from all the wavelengths.

The cost of ADMs represents the dominant cost of the network infrastructure [25]. In general the solution proposed in order to reduce the number of ADMs is an upgrade of the point-to-point network architecture. This upgrade consists in providing each node with an *Optical Add-Drop Multiplexer* (OADM) (Fig. 2). An OADM allows the optical signal to bypass a node. By properly positioning the time-slot channels on the wavelengths the number of ADMs can be reduced. If a node does not need to receive or transmit traffic on a wavelength, the associated ADM can be removed.

In this article, we study a different node architecture. It is described in the next section and depicted in Fig. 3. Despite the difference between these architectures we will see that our study is similar to the reduction of the number of ADMs.

Methods which propose a solution to the time-slot channels assignment are referred to as grooming methods. Traffic grooming and wavelength assignment have been proposed, as a solution to the dimensioning problem, on many topologies, e.g. mesh networks [13], ring networks [18] [17] [4] [12] [9] [6] [14] and multi-ring networks [20]. In [6] the authors described the problem of traffic grooming and proved it NP-complete. An Integer Linear Problem was formulated in [19] and the problem can thus be optimally resolved for small instances. Under special traffic constraints optimal solutions have been provided for greater instances. For example, the authors of [9] furnish an optimal solution for all-to-all traffic with identical traffic rates. Lower bounds have been computed in [24]. Finally, heuristics were introduced in [18] [6]. In [18] the authors proposed heuristics to minimize the total number of ADMs. In [6] the presented method aims to minimize the number of ADMs at the node where this number is maximum.

In [17] [12], the authors considered an architecture provided with one or more *Digital Cross Connect* (DXC), also called hubs. These electronic equipments allow traffic to be switched from one wavelength to another. A DXC is provided with an ADM for each wavelength. An optical version referred as *OXC* (Optical Cross Connect) is introduced in [20]. An OXCs allow the optical signal to bypass the hubs. In both electronic and optic cases the authors studied the impact of high grooming capacity provided by hubs on the dimensioning. More recent studies [23] were made into mesh networks equipped with OXCs. These studies aim to reduce the power consumption using traffic grooming and a sleeping method (i.e. inactive routers can be turned off).

Metropolitan optical networks were studied in many projects as the HORNET project [21] which mainly focused on the architecture of an opto-electronic node under assumption of the bursty Internet traffic. The RINGO project [10] proposed a slotted mesh topology. The two following projects were oriented principally to optical rings: the FLAMINGO project [8] which considered the packet switching over WDM in an all-optical environment and the DAVID [11] project. The latter studied a slotted metropolitan multi-ring paying particular attention to ADD & DROP wavelength assignment problems [2].

To finish we note that a survey of the research papers dealing with OADM technologies was made in [17].

III. All-optical nodes

We describe here a node architecture for WDM/TDM metropolitan networks, known as *Packet Optical Add-Drop Multiplexer* (POADM) [7]. Like the OADM architecture, it allows us to reduce the power consumption because it allows the optical signal to bypass nodes. Both the OPEX and the ecological impact can thus be reduced. However OADM and POADM have different internal structures. We compare these structures and outline the fact that using POADM potentially allows us to reach a smaller CAPEX cost.

An ADM can add/drop traffic to/from a wavelength. It can be seen as the composition of a *receiver* (Rx) and a *transmitter* (Tx). The term of *transceiver* (TRx) is commonly used to describe an ADM. The OADM architecture uses TRx. A node has thus the capacity to read and write on a subset of wavelengths. Reading on a wavelength does not necessarily imply writing on the wavelength and vice versa. In POADM architecture Rx and Tx are separated. *Tunable Lasers* (TL) are used to inject the information into the wavelengths and the node requires only one Tx. Fig. 2 and Fig. 3 depict nodes using an OADM device and a POADM device, receptively. In both cases the green wavelength (the one in the middle) bypasses the node. In this simple example, the node with OADM has two Txs whereas the node with POADM has only one Tx. Using POADMs allows us to reduce the CAPEX cost.

The dimensioning of a network with a POADM node architecture consists in minimizing both the number of wavelengths used and the number of Rxs. We note that minimizing the number of Rxs is not equivalent to minimizing the number of ADMs in a network with OADM node architecture. As a consequence, new dimensioning problems have to be explored.

IV. The Minimum WaveLength Problem

In this section, we propose to minimize the number of wavelengths of a network with POADM node architecture. In Section III, we saw that to minimize the total number of receivers was important in order to reduce both the OPEX and

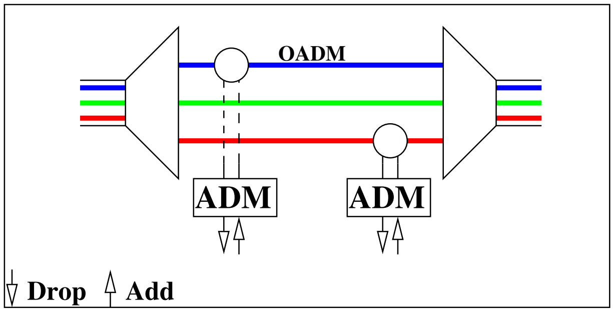

Fig. 2. OADM node architecture

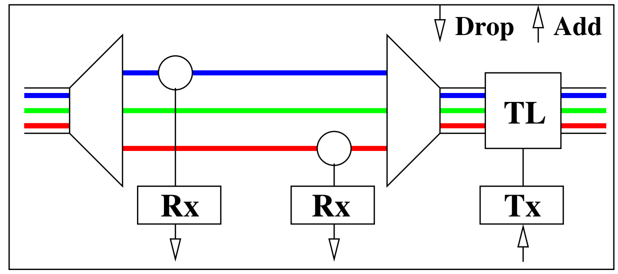

Fig. 3. POADM node architecture

CAPEX costs. In the problem introduced here as a decision problem, the number of receivers is considered as a constraint instead of a parameter. Indeed, we fix the number of receivers to its minimum for each node.

Problem: MINIMUM WAVELENGTH PROBLEM

Data:

- An elementary circuit [3] $G = (V, E)$.
- A traffic matrix T with $T[i, j]$ the amount of traffic sent from node i to node j.
- A set $\lambda = \{\lambda_1, \lambda_2, ..., \lambda_K\}$ of wavelengths and $K \in \mathbb{N}$.
- A wavelength capacity $C \in \mathbb{N}$ (= grooming ratio).

We call *assignment* the operation which decomposes T into a set of K matrices T_k of the same dimension as T and associates T_k to a wavelength $k \in \lambda$ of an optical ring.

Question: Is it possible to find an assignment of the traffic T on the wavelengths λ that respects simultaneously the *flow*, *capacity* and *receiver* constraints?

Flow constraint: For any couple of nodes (i, j), the amount of traffic carried on each wavelength has to be equal to the total amount of traffic between i and j:

$$\forall i, j \in V, \sum_{k \in \lambda} T_k[i, j] = T[i, j].$$

Capacity constraint: Let $load_k(x)$ be the load of the arc $x \in E$ for the wavelength k. In other words $load_k(x)$ is equal to the amount of traffic carried by the arc x on the wavelength k. $load_k(x)$ cannot exceed the capacity C:

$$\forall k \in \lambda, \forall x \in E, \text{load}_k(x) = \sum_{i,j \ s.t. \ x \in path(i,j) \in G} T_k[i, j] \leq C.$$

Receiver constraint: Let w_i^- be the set of wavelengths on which a node i has to read in order to receive all the traffic sent to it. The $|w_i^-|$ indicates the minimal number of Rxs needed for the node i.

$$\forall i \in V, w_i^- = \{k \in \lambda | \forall s \in V, T_k[s, i] \neq 0\},$$

$$\forall i \in V, |w_i^-| = \left\lceil \frac{\sum_j T[j, i]}{C} \right\rceil .$$

V. COMPLEXITY

We use the *Bin Packing Problem* (BPP) [15] to prove that the MWLP is NP-Complete.

Problem: BIN-PACKING PROBLEM

Data:

- A set of boxes $B = \{B_1, B_2, ..., B_l\}$
- A box capacity $C_B \in \mathbb{N}$
- A set of elements $X = \{X_1, X_2, ..., X_m\}$
- A function $b : X \rightarrow \{1, 2, ..., C_B\}$ which associates a volume to each element of X.

Question: Is it possible to find a partition of X into l non-empty subsets so that for each subset the sum of the element volumes is less than or equal to C_B?

Theorem 5.1: The MWLP is NP-Complete.

Proof: Given an instance of MWLP and an assignment of the traffic T on λ, we can determine if this assignment verify all three constraints in polynomial time. The certificate of MWLP is in P.

Let us consider an instance of the BPP. For each element of X we create a node in an initially empty elementary circuit G. This node is called X_i as a reference to the associated element. We then add to G the node S which will be the origin of all traffic. Nodes in G are ordered so that $S \prec X_1 \prec ... \prec X_m$ where $X \prec Y$ means that X is placed before Y in the ring. The traffic matrix is built as follows: $T[S, X_i] = b(X_i)$. All other T elements are equal to zero. We now fix the box B_i to the wavelength λ_i. The wavelength capacity $C = C_B$. At this moment we obtain a proper instance of MWLP. We now show that if BPP has a solution, then MWLP has a solution and reciprocally. We see that all the traffic is passing through the arc between S and X_1 on the different wavelengths. Obviously, we are able to say that if the assignment of the traffic T on λ verifies our three constraints on the arc, then this assignment is a solution to MWLP.

Since an element X_i is associated with a node in G and cannot be cut into several parts, the traffic passing through X_i is assigned to one wavelength. In other words X_i is in one and only one box and, consequently, the *flow constraint* is respected.

For each wavelength the amount of traffic on the arc (S, X_1) is equal to the sum of the element volumes in the associated box. The sum is less or equal to $C_B = C$. Thus the *capacity constraint* is respected:

$$\forall k \in \lambda, \text{load}_k((S, X_1)) = \sum_{i=1}^{M} b_i \cdot \chi(X_i, k) \leq C, \quad \text{where}$$

$$\chi(a, k) = \begin{cases} 1, & \text{if } a \in X \text{ is packed in the box } B_k, \\ 0, & \text{otherwise.} \end{cases}$$

All the traffic received by the nodes X_i originates from S. Since the traffic is assigned to one and only one wavelength, any node, S excluded, has one receiver. The *receiver constraint* is respected:

$$\forall i \in C_B - \{S\}, \sum_{k \in \lambda} \chi(i, k) = |w_i^-| = 1,$$

$$\sum_{k \in \lambda} \chi(S, k) = |w_S^-| = 0.$$

If there exists an assignment of traffic with the matrix T on the wavelength λ which respects all the three constraints, then a traffic from S to X_i is associated with one and only one wavelength. The set of wavelengths is then a partition of traffic $T_k(S, X_i)$ in K subsets and each of these subsets has a size less or equal to C. The BPP can be reduced polynomially to MWLP. Moreover, a solution of the BPP is a solution for the MWLP and reciprocally, a MWLP solution is a BPP solution. MWLP is thus NP-Complete. ■

VI. The heuristic algorithm

In this section we introduce a heuristic algorithm which solves the MWLP. This algorithm assigns groups of point-to-point connections (requests) to wavelengths. We explain how to proceed in order to obtain a solution that minimizes the number of wavelengths while satisfying the three constraints.

Given a n-node ring network, with nodes numbered from 1 to n, we consider each wavelength as a n-dimension cube. The dimension i is associated with the arc i (i.e. the arc between nodes i and $i + 1$). The length of the edges of this cube is equal to C. Such a cube is called a *box*.

We consider a request as a n-dimension vector. The request from a node x to a node y is written as $r^{(x,y)}$. The size of a request is equal to the amount of traffic carried by this request. We note $s(r^{(x,y)})$, the size of the request $r^{(x,y)}$. For example, in a 4-node ring we consider the request $r^{(1,3)} = (2, 2, 0, 0)$. The request $r^{(1,3)}$ passes through the arcs 1 and 2 but not through the arcs 3 and 4 and $s(r^{(1,3)}) = 2$. A *unitary* request is a request with size equal to one.

The *length* of a request is the number of arcs between its origin and its destination. The length of request $r^{(1,3)}$ is 2.

A set of requests R *fits* in a box if and only if :

$$\forall i \in [1, n] \sum_{r \in R} P_i(r) \leq C, \tag{1}$$

where $P_i(r)$ is the projection of vector r on the dimension i.

In order to satisfy the capacity and receiver constraints, a set of requests destined to the same node d may have to be partitioned into a small number of subsets. Each subset has to fit in a box (Eq. 1) and the number of subsets created for a node d has to be equal to $|w_d^-|$.

The number of Rxs for each node has to be minimal. We thus group the requests according to their destination. To create the subsets of requests for a destination d, we proceed as follows. Firstly, each request of size x is divided into unitary requests. Secondly, we sort requests in a decreasing order according to their lengths. Thirdly, we constitute groups of C unitary requests starting with the longest requests. The last group may contain fewer than C unitary requests. This sequence of operations has to be made for each destination.

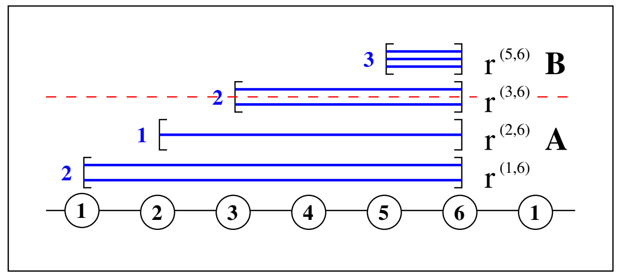

Fig. 4. Subsets of requests dedicated to the node 6 in a 6-node ring

For example, in Fig. 4 we study how to create the subsets of requests for the node 6 in a 6-node ring with $C = 4$. The sizes of the requests are: $s(r^{(2,6)}) = 1, s(r^{(1,6)}) = s(r^{(3,6)}) = 2, s(r^{(5,6)}) = 3$. The total amount of traffic received by node 6 is eight which means that we have to create two subsets. Fig. 4 depicts the decreasingly sorted unitary requests. The dotted line separates the two subsets. The optical technology allows one to split a request into several sub-requests. Each sub-request should have a size greater than or equal to one. In our example $r^{(3,6)}$ is split.

A subset of requests can be also seen as a n-dimension vector which is equal to the sum of the requests which it is composed of. In the previous example the two subsets created are $A = (2, 3, 4, 4, 4, 0)$ and $B = (0, 0, 1, 1, 4, 0)$.

An *element* is a subset of requests which fits in a box. To pack elements into the boxes (i.e. to assign subsets to wavelengths) we use the *First Fit Decreasing* method (FFD) [22]. In this method we first sorted the elements by size in a decreasing order then packed into the first box available into which they fit. The first element to be packed is thus the biggest. We note that the term *biggest element* may designate the element which is the most difficult to pack. For one dimension problems, such as a *Knapsack problem* [15], the size is easy to determine as we take either the height or the weight. For this heuristic algorithm we propose two methods in order to compute the size of the elements.

We consider the n-dimension element $x = (x_1, x_2, ..., x_n)$.

In the first method, the size of an element is equal to the sum of the sizes in each dimension, $s(x) = \sum_{i=1}^{n} x_i$. In our example (Fig. 4) $s(A) = 17$ and $s(B) = 6$.

In the second method we consider the total load $load_i$ of each arc i (each dimension) in the network. Indeed, if the load of an arc i is high and if for an element the size of its dimension i is great, then this element is difficult to pack. With this method the size of an element is $s(x) = \sum_{i=1}^{n} x_i \cdot \text{load}_i$.

VII. Results

In this section we discuss the performance of the heuristic algorithm introduced above. We present results for two series of experiments. The first one aims to show the influence of different sizes of connections on the heuristic performance. The second one aims to show the influence of different spatial distributions of the traffic (i.e. some nodes receive a lot of traffic while others do not).

We performed the following experiments on small (10 nodes), average (50 nodes) and wide (100 nodes) rings. The heuristic performance exhibits the same tendencies in all cases we present regardless of the number of nodes.

In a first time we present results computed using the First Fit method without have sorting out the elements. Next, we show the results computed with the FFD method. In this case we use two different methods to compute the element size.

A. Connection size

We generate all-to-all traffic and use probabilistic distributions to determine the amount to be sent between the nodes. We study here the influence of four distributions on the size of the connection (uniform, exponential, normal: N$(\mu, 20\%\mu)$ and N$(\mu, 50\%\mu)$). Fig. 5 depicts the evolution of the average utilization of the bandwidth depending on the ratio of the average size of connection (μ) and the capacity of the wavelength (C). We choose to study this ratio since both the capacity of the wavelength and the average size of connection may increase in future networks. The means are estimated with 3% precision and the confidence coefficient $\alpha = 0.05$.

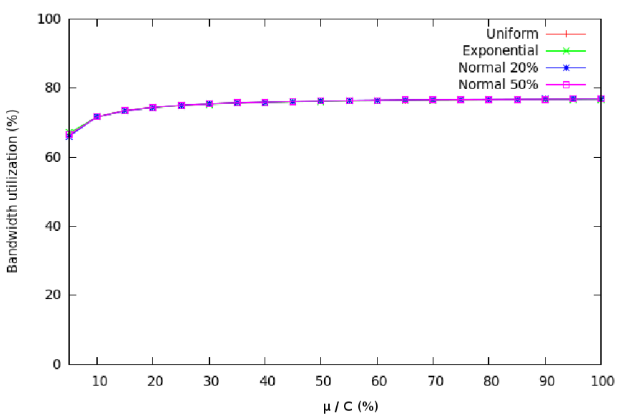

Fig. 5. Bandwidth utilization for all-to-all traffic with size of connection randomly distributed (the curves are identical for all four distributions)

Firstly, we see here that when the ratio $\frac{\mu}{C}$ increases, then the bandwidth utilization also increases. Secondly, despite the fact that we use different distributions to compute the size of a connection, the four curves overlap perfectly.

When the ratio $\frac{\mu}{C}$ is high, the elements generated from the pyramid are more "regular". Such elements are indeed composed of few connections. Consequently, the elements are easier to pack into the wavelengths. In other words the unused space is easily used to pack other elements.

An element is composed of a sum of connections. The element size is a sum of iid values and thus follows a normal distribution.

B. Spatial distribution

We randomly choose origin-destination couples in order to show the influence of a spatial distribution on the performance of our heuristic algorithm. Fig. 6 depicts the evolution of the average utilization of the bandwidth depending, as before, on $\frac{\mu}{C}$. We use two spatial distributions: uniform and *Rich Get Richer* (RGR) distribution [1]. The RGR distribution is chosen to represent the real traffic condition. In a ring network some nodes may attract more traffic (e.g., video base server, backbone access nodes). The sizes of the connections are uniformly distributed. The performances of the heuristic algorithm are almost identical in both the cases and reach a bandwidth utilization of 70 percent.

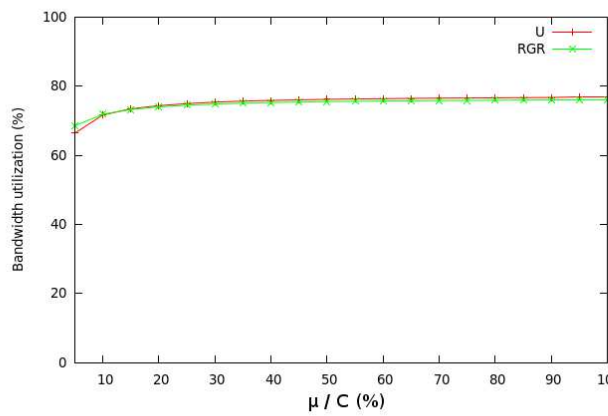

Fig. 6. Bandwidth utilization for spatially distributed traffic

In Fig. 7 we consider the elements which are packed using the FFD method. The element size is computed using the first method introduced in the previous section. We note that the performances of our heuristic algorithm improve when the elements are sorted in this way and reach respectively 87 percent and 97 percent of the bandwidth utilization for RGR and normal traffic condition. We also see that the heuristic algorithm uses the bandwidth for an uniform distribution more effectively than for an RGR distribution.

On both Figs. 8 and 9 we take as an example a network with 100 nodes (numbered from 1 to 100). We consider the amount of traffic R_i received by each node i which is expressed as a number of occupied wavelengths because all but possibly one

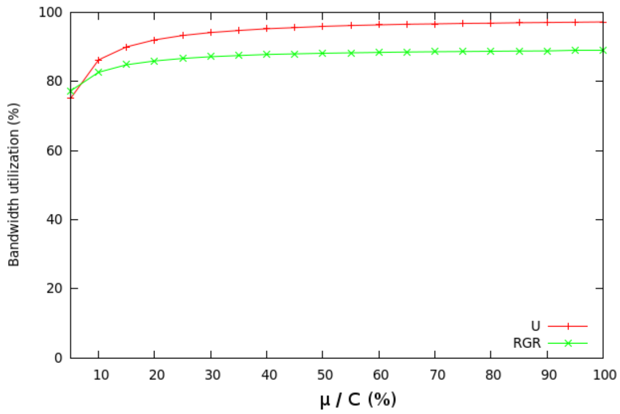

Fig. 7. Bandwidth utilization for spatially distributed traffic with sort

are completly filled up (curve on the bottom). We compare the use of the bandwidth by our heuristic algorithm (curve on the top) with the use of the bandwidth by a lower bound (curve in the middle). λ^* is the number of wavelengths used by an optimal solution. It is obvious that $\lambda^* C \geq \max_i(R_i)$. We take thus $\max_i(R_i)$ as the lower bound. λ^*_{uni} and λ^*_{rgr} is the number of wavelengths used respectively by an optimal solution for uniform distribution and an optimal solution for RGR distribution for the same total amount of traffic sent. We have $\max_i(R_i^{\text{uni}}) \leq \max_i(R_i^{\text{rgr}})$ since uniform traffic is more regular. $\lambda^*_{\text{uni}} \leq \lambda^*_{\text{rgr}}$. Fig. 8 depicts results computed for the uniform distribution. For this distribution our heuristic algorithm uses only 3 percent more of wavelengths than the lower bound. Fig. 9 depicts results computed for RGR distribution. For this distribution our heuristic algorithm uses only 1,7 percent more of wavelengths than the lower bound. We show with these experiments that our heuristic algorithm performs well under uniform traffic conditions and even better under RGR traffic conditions.

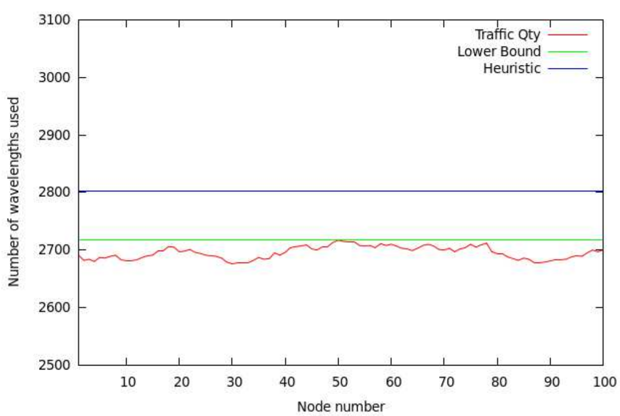

Fig. 8. Results for uniform spatial traffic vs lower bound

VIII. Conclusion and perspectives

We have studied a dimensioning problem for all-optical metropolitan rings called *Minimum WaveLength Problem* (MWLP). We want to minimize both the number of wavelengths and the number of receivers used in the network. We have proved that the construction of an optimal solution for this problem is NP-Complete. We proposed a heuristic algorithm based on greedy multi-dimensional packing. Finally, we have studied the performance of our heuristic algorithm using random traffic matrices. We observed that our heuristic algorithm performs well under realistic traffic conditions. We are currently working on the approximability of the MWLP. We also plan to study the extension of the MWLP to the multi-ring networks.

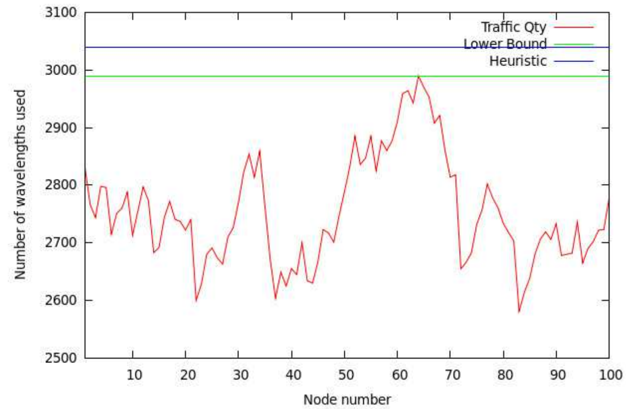

Fig. 9. Results for RGR spatial traffic vs lower bound

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